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33p THE SOLAR EXTREME ULTRAVIOLET RADIATION (1-400Å) ~~X64-11773~~

By

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INTRODUCTION:

The study of the extreme ultraviolet (EUV) radiation from the sun is, and since 1958 has been, an active and dynamic field or research. There have been a dozen or more rocket flights in addition to the first Orbiting Solar Observatory to observe the solar spectrum in wavelengths near 300A. Also, in the case of wavelengths in the neighborhood of 10A, numerous rocket measurements have been made in addition to observations from three highly successful satellites; Solar Radiation-1, Orbiting Solar Observatoyy-1, and Ariel-1. Most of these measurements have been carried out by groups at the Naval Research Laboratory, Air Force Cambridge Research Center, Goddard Space Flight Center, University of Colorado, University of Leicester and University College, London. In general the satellite observations discussed below refer to OSO-1, not because they are any more significant than other data but rather because the OSO-1 measurements are more familiar to the author.

Submitted for Publication

SOLAR X-RAYS (1-10A)

Practically all of the early studies of solar X-rays near 10A were made by the group at the Naval Research Laboratory (Friedman, Lichtman and Byram [1] , Byram, Chubb and Friedman [2].) The research in 1956 utilizing a rockoon launch from an LST in the Pacific Ocean led to the discovery of a significant enhancement of soft X-rays associated with a small solar flare (Chubb, Friedman, Kreplin and Kupperian [3].) The following year, a number of Nike Deacons were launched during solar flares confirming the causality relationship between the X-ray enhancement and radio fadeout. In fact, with one of these flights X-rays were detected 63.5 Km above the earth's surface, (Friedman, Chubb, Kupperian, Kreplin and Lindsay [4].) Since these observations, numerous other rocket measurements have been made by NRL, the University of Leicester group and Goddard Space Flight Center, to study solar X-rays. The rocket results have been reconfirmed and/or superseded by satellite observations.

Three satellites have made measurements of solar radiation at wavelengths near 10 Angstroms. These were the Solar Radiation-1 (SR-1), launched June 22, 1960, (Kreplin, Chubb, and Friedman [5]), followed by the first Orbiting Solar Observatory (OSO-1), launched March 7, 1962, (White, [6]), and Ariel, launched April 26, 1962 (Pounds, Willmore, Bowen, Norman and Sanford [7]).

Two types of detectors were used in these measurements. SR-1 and OSO-1 utilized ion chambers which responded to wavelengths shorter than 8A and 11A, respectively. Ariel, on the other hand, carried proportional counters which measured the wavelength distribution as well as intensity from 3 to 15A. Since OSO-1 and Ariel were in orbit simultaneously, some cross checks of data have been possible.

The Orbiting Solar Observatory-1, due to the use of "on board" tape recorders, provided observations that were as near continuous as possible for a low altitude (600 Km) circular orbit nearly equatorial. This continuity, combined with adequate experimont sensitivity, made it practicable to study the "quiet" as well as the slowly-varying component of the sun's X-ray emission.

In order to calculate the full scale sensitivity of the OSO-1 experiment, the spectral shape measured by Pounds, Willmore, et al [7] for April 27 was chosen as the most appropriate. This spectrum is consistent with a $2.8 \times (10)^6$ ^oK plasma with wavelengths in the 3-11A interval contributing to the output current of the ion chamber whose response is shown in Figure 1. The full scale sensitivity for 3-11A X-rays is then found to be 1.8×10^{-3} ergs cm^{-2} sec^{-1}. For comparison with the earlier SR-1 measurement (Kreplin et al [5]) over bandwidths specified as 2-8A, the full scale sensitivity of the OSO-1 experiment is 3.6×10^{-4} ergs cm^{-2} sec^{-1} .

The sun was most cooperative in that during the first week after launch, and for a similar period one solar rotation later, the sun was very quiet. The sunspot number was reported as

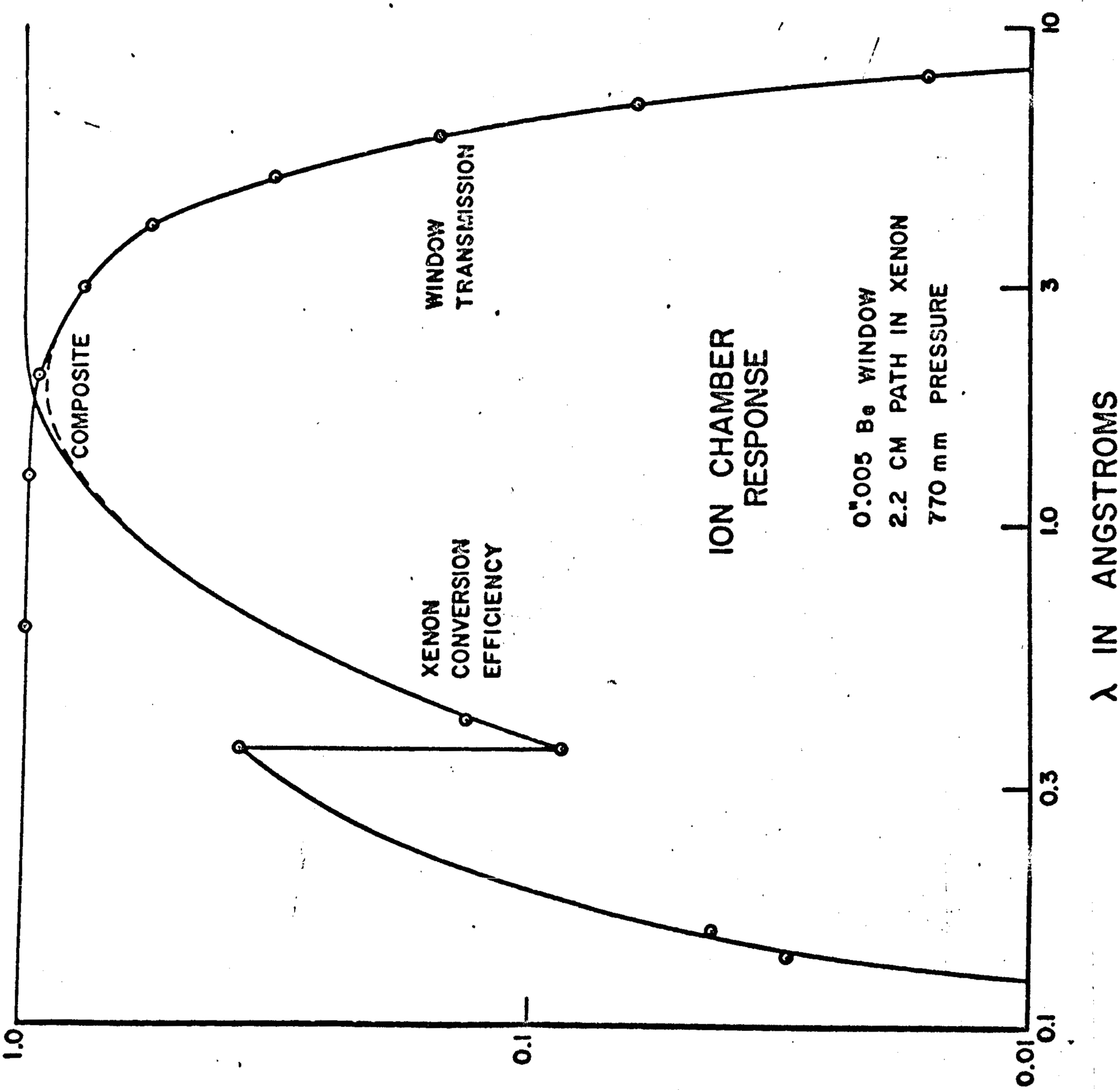


Figure 1. OSO-1 Ion Chamber Response

11 on March 11, 1962, with a Ca+ plage weighted area of 2×10^3 (in millionths of solar hemisphere). The subsequent rotation of the sun brought several centers of activity onto and across the visible disk so that on March 28, 1962, the sunspot number was approximately 90 and the Ca+ plage weighted area was 5.5×10^4.

During the next rotation on April 6, 1962, the lowest X-ray flux encountered by OSO-1 was measured. For wavelengths less than 8A the flux was 3.6×10^{-5} erg cm^{-2} sec^{-1}; for wavelengths less than 11A, 1.8×10^{-4} erg cm^{-2} sec^{-1}. This may be considered as an upper bound on the X-ray flux from the "quiet" sun. This flux occurred at a time when only 3 small plages were visible on the disk and there was no limb activity. Such a "quiet" reading is shown in Figure 2, where for about one hour the X-ray flux is practically constant.

It is of interest to note that such quiet orbits were rare. Examination of several hundred orbits disclosed only six hours (six orbits) in which the X-ray flux was almost constant, varying by less than 5% during the hour period. It is concluded that the X-ray emission from the sun is varying almost continually on an hourly basis.

As the rotation of the sun carried several centers of activity onto and across the visible disk the effect of plage activity on the solar X-ray flux was observed. A comparison of the slowly varying component of the 10A X-ray flux with 2800-Mc radiation and plage activity is shown in Figure 3, confirming that localized

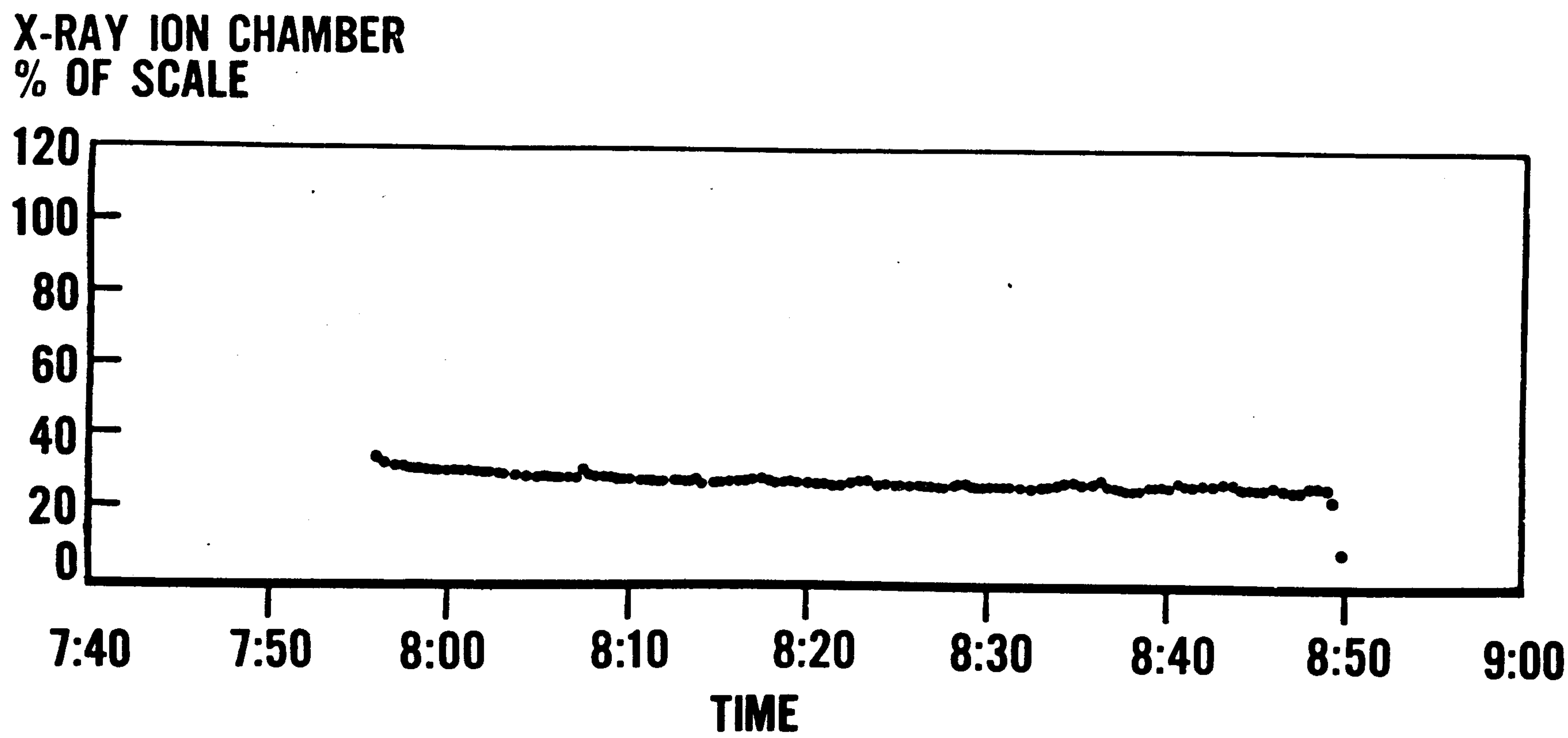


Figure 2. OSO-1 Observation of Solar X-ray Flux for a Quiet Period

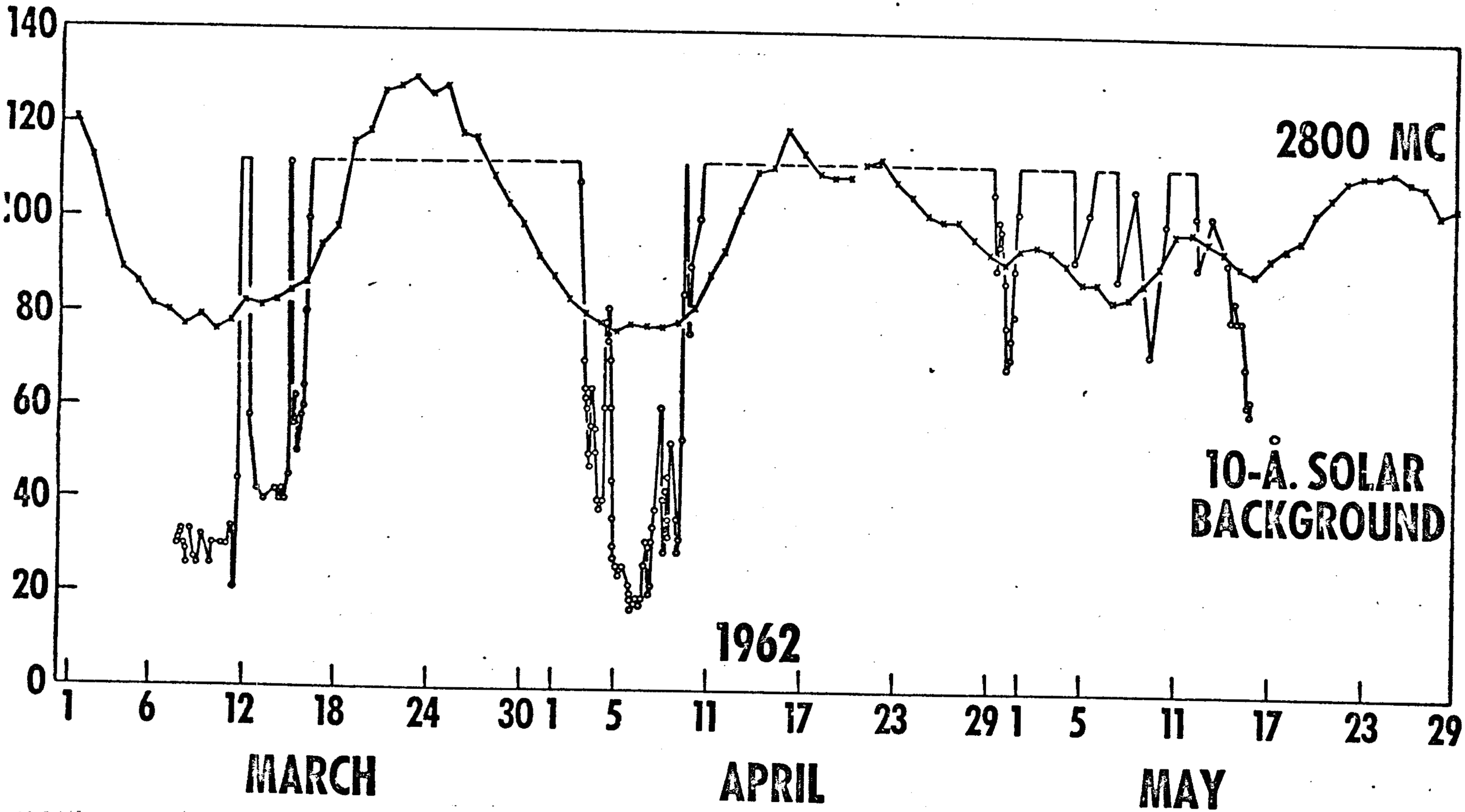


Figure 3. Comparison of X-ray Flux with 2800-Mc Radio Measurements

sources of solar X-rays are associated with centers of activity. It can be seen that the smoothed X-ray flux correlates with the excess of the 2800-Mc flux above a background of 75 flux units appropriate for the "quiet" sun at that phase of the solar cycle (Covington and Harvey [8].)

A word of caution concerning the flux values quoted above, and generally, in the literature is in order. Both the Ariel [7] and OSO-1 [6] data are not explainable on the basis of a continuum radiation from a hot plasma. The problem is that a calculation of the thermal emission from even a 3 million degree plasma falls short of the measured intensities, assuming the entire corona is at that temperature. White [6], using estimated upper limits of electron density and temperature supplied by Billings [9] from observations of plages on the sun, April 6, 1962, and assuming the volume of a plage region to be a "pillbox" with a height equal to the plage radius, calculated the X-ray flux from the plage. Even then the continuum radiation was low by an order of magnitude. It was concluded that the major portion of the flux must be due to line emission. Pounds, et al.[7] using Ariel data, arrived at a similar conclusion. Since the line spectra energy distribution is not known, quoted flux values may be in considerable error.

In addition to these quasi steady-state conditions, transient events (X-ray flares) lasting from a few minutes to a couple of hours were observed by SR-1, OSO-1 and Ariel. Several such events observed by OSO-1 are shown in Figure 4. The event (Orbit #6) shown in Figure 4 contained a total energy below 11A of about $2\ (10)^{27}$ ergs. The flux at the maximum was approximately

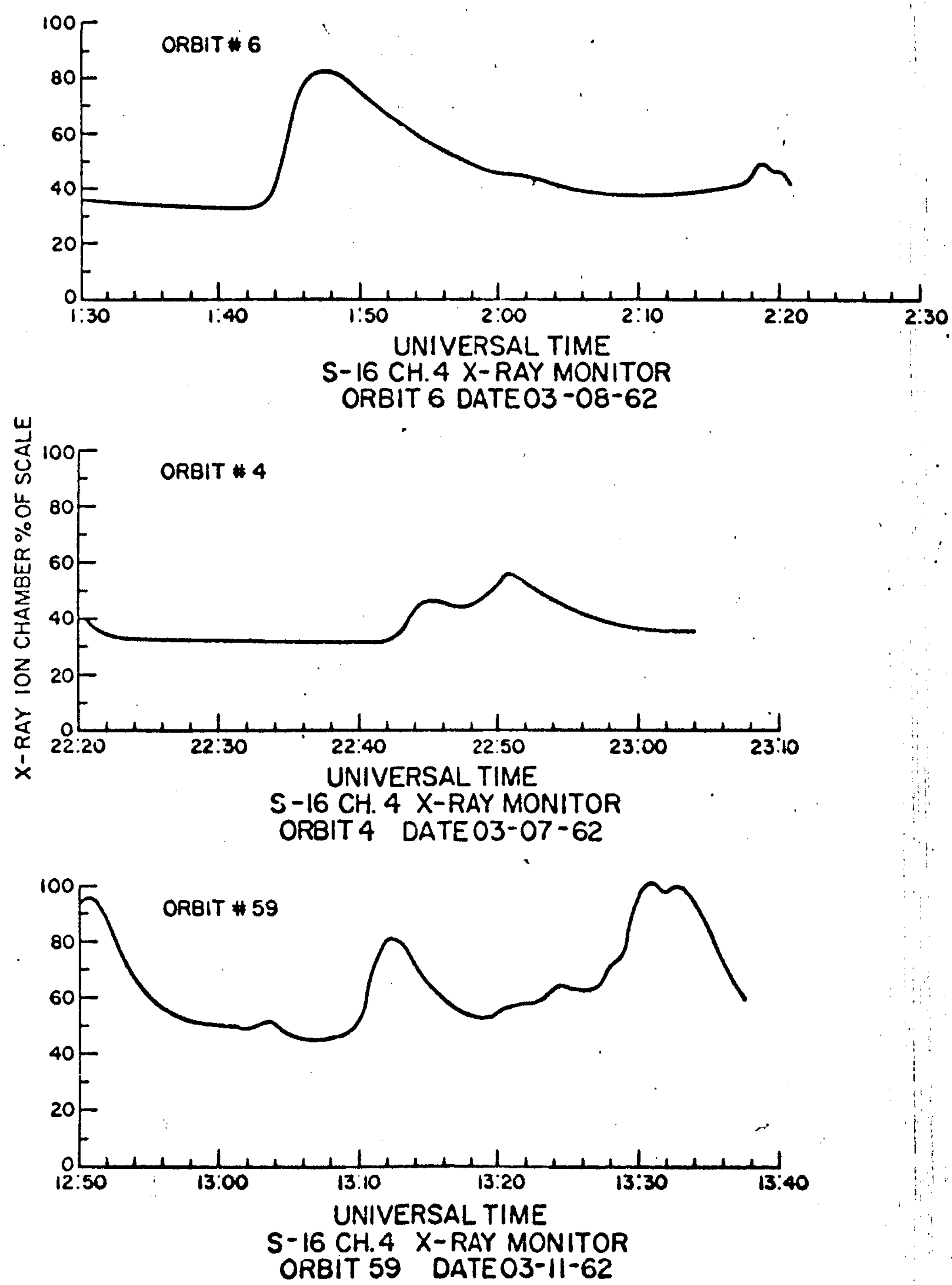


Figure 4. Typical Transient X-ray Events Obsserved by OSO-1

1.6×10^{-3} ergs cm^{-2} sec^{-1} in the interval 3-11A or 3.0×10^{-3} ergs cm^{-2} sec^{-1} for 2-8A. This was not a very large event compared to some that have been observed, however, other than the OSO-1 observations, there have been only one or two flares for which a complete time history of X-ray emission has been recorded.

Another X-ray event (Figure 4, Orbit #4) occurred simultaneously with an H-alpha flare reported to have begun at approximately 22:42 UT, to have reached maximum intensity at 22:44 UT and to have ended at 22:55 UT. Although the X-ray enhancement coincided fairly well with the beginning of the H-alpha event, the peak X-ray intensity was observed after the H-alpha maximum and X-ray enhancement existed after the reported end of the H-alpha flare. Of the X-ray flares observed by OSO-1, residual X-ray enhancement after the end of the H-alpha flare was quite common. The X-ray data for Orbit #59 (Figure 4) illustrates the great variability of solar X-ray flux. Although not shown, during several orbits significant variations in the X-ray flux were observed to take place in the order of a second.

Practically all the flare energy spectrum data available has been recorded by Ariel. The flare associated X-ray spectrum was observed to intensify and harden compared with the pre-flare spectrum with the degree of enhancement varying widely from flare to flare; sometimes having no counterpart in H-alpha. In addition, X-ray enhancements appeared to be much more frequent.

To illustrate, the 7-day interval between launch of OSO-1 and March 14, 1962 (at which time the rising of plage #6370 on the east limb supplied enough X-ray emission to carry the experiment off-scale), approximately 60 X-ray flare events (Figure 5), lasting from 10 minutes to 1 hour were seen, and 4 events were seen to last about 5 hours. During this same interval (1620 UT March 7, 1962, to 1620 UT March 14, 1962) some 33 H-alpha flares were reported by ground-based observatories. Of these H-alpha flares, 6 would have been unobservable from OSO-1 for various reasons (satellite night, failure to command data storage readout, etc.). Of the remaining 27 H-alpha flares, 3 occurred while the X-ray experiment was still off-scale because of a previous large event. This leaves 24 H-alpha flares which can be tested for correlation with the X-ray flares. Of this group of 24, it appears that 11 correlate well, 3 definitely have no counterpart in X-rays, and the remaining 10 are doubtful because of insufficient data or an excessive time difference (10 minutes). Conversely, there are 6 full-scale or greater X-ray events for which no H-alpha flare was reported, even though observations were presumably being made at the time. Certainly more observations will be required before a definite statement can be made regarding a correlation or lack thereof, between H-alpha flares and X-ray flares.

In looking for correlations with Sudden Ionospheric Disturbances, all X-ray events exceeding the full-scale saturation level were barely detectable (if observing conditions permitted),

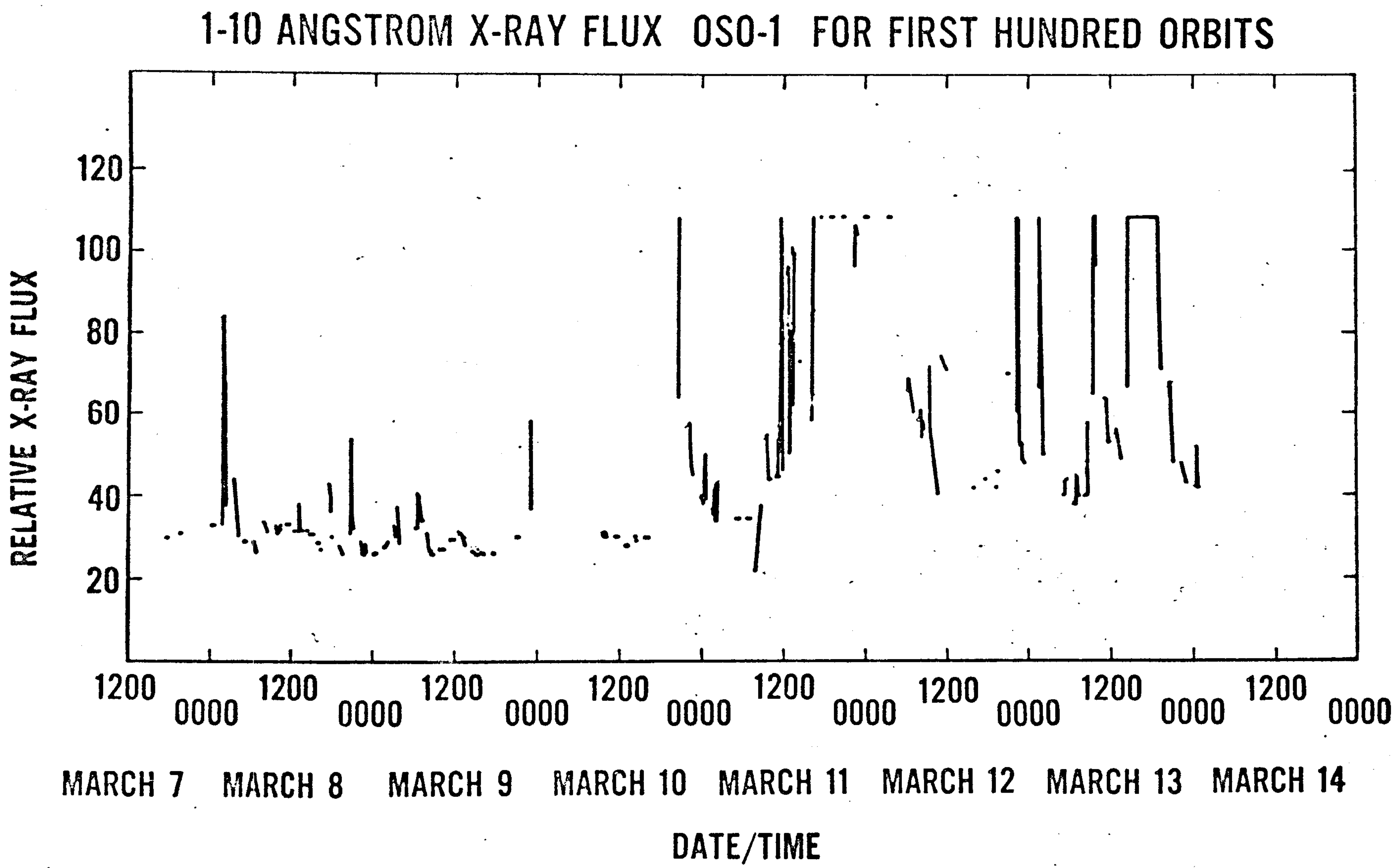


Figure 5. X-ray Events for Period March 7 to 14, 1962, Observed by OSO-1

in Sudden Phase Anomaly data for VLF transmission via the D layer. Only the large event of 13 March was seen in ionospheric indices other than SPA's. Correlation with transients in the 2800-Mc solar flux is good; but again, full scale X-ray events are represented by extremely small events (1 to 2 flux units) in the 2800-Mc data, Figure 6.

SR-1 results have led to the conclusion (Kreplin et al [5]) that if the X-ray flux $\lambda < 8A$ exceeded 2×10^{-3} erg cm^{-2} sec^{-1} radio fadeout and other SID phenomena occurred simultaneously. It was also observed that active prominence regions, bright limb surges and small limb flares produce X-ray events that resemble those accompanying disk flares. For example, SR-1 observed, on July 24, 1960, a long duration X-ray event of sufficient intensity to produce ionospheric disturbances accompanying a rising limb prominence. The event was recorded photographically as well as in its X-ray emission. Enhanced X-ray emission was observed for about 8 hours with the mean flux reaching 5×10^{-3} ergs cm^{-2} sec^{-1} . There was no visible flare, however, ionospheric records detected a radio fadeout that occurred simultaneously with the increase in X-ray emission and lasted until the X-ray intensity returned to a normal level.

SOLAR RADIATION (50-400A)

To observe the spectrum below about 500A it is necessary to use instruments in grazing-incidence. The first successful flight of an instrument such as the grazing-incidence spectrograph

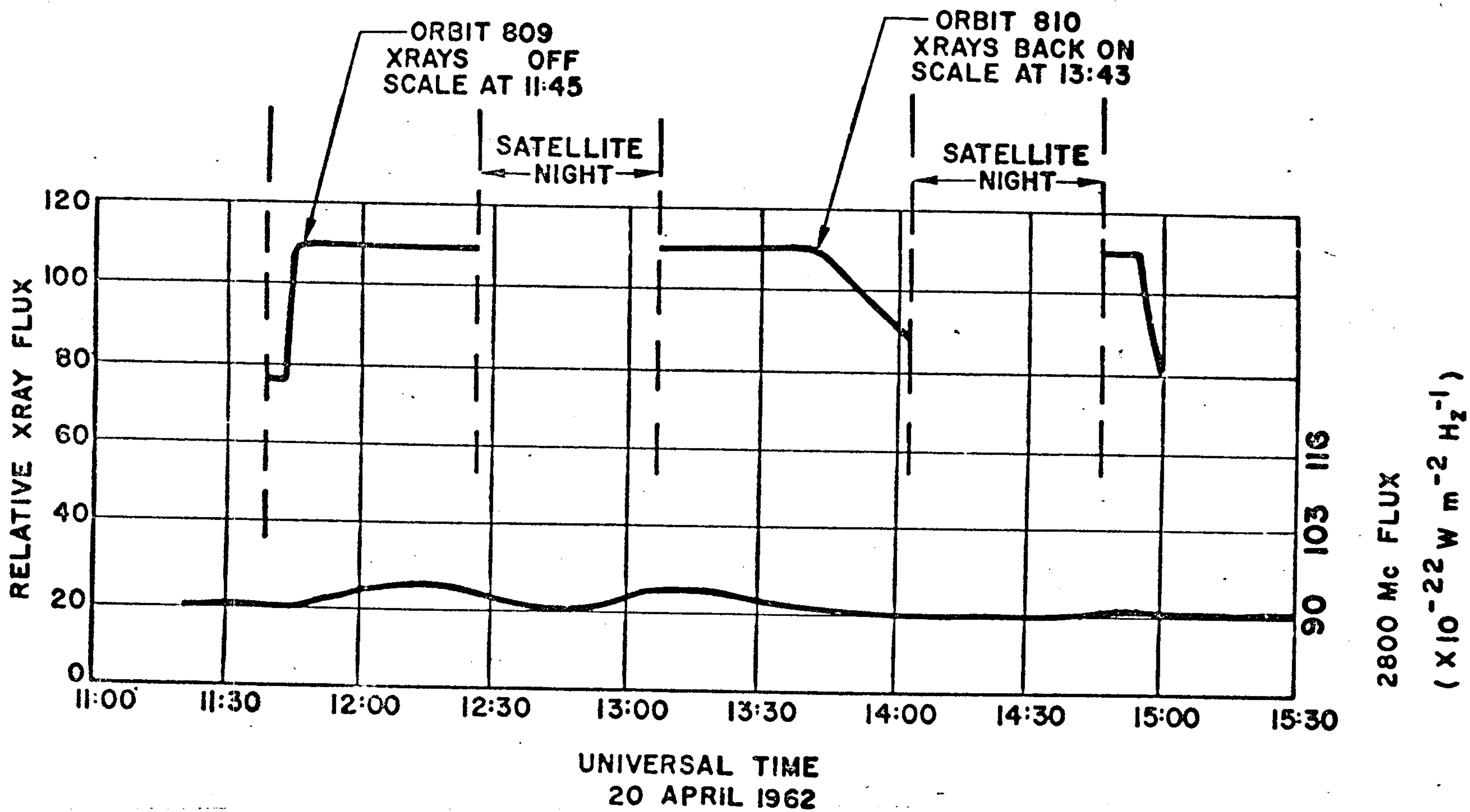


Figure 6. Comparison of X-ray Events in X-rays and 2800-Mc Flux Showing Larger Percentage Change in X-rays

was made by Violett and Rense [10] of the University of Colorado on June 4, 1958. This was followed by a second flight on March 30, 1959. The records of these flights show a large number of EUV emission lines, including the 304A line of Helium II Lyman-alpha. Unfortunately, due to the large amount of scatter-light which is inherent in grazing-incidence, interpretation of the data was extremely difficult.

By using photoelectric detection with a threshold at about 1400A, Hinteregger and his colleagues at Air Force Cambridge Research Center have been able to reduce the scattered light problem. Using grazing-incidence monochromators with photo-electric detection and telemetering the data during flight, the AFCRC group has had numerous successful rocket flights. Their earliest record of the EUV below 400A was obtained January 29, 1960, followed by a flight on August 23, 1960 (Hinteregger [11]; Hall, Damon and Hinteregger [12]). The spectra shown in Figure 7 shows an increase in continuum intensity near 200A that may be in part the Lyman limit of He II at 228A. The photoelectric telemetered spectra agrees well with a photographically obtained spectra (Figure 7) of Tousey and co-workers (Tousey et al [13]) June 21, 1961, who used an aluminum filter 1000A thick to eliminate scattered light in a grazing-incidence spectrograph. This filter transmits from the $L_{II,III}$ edge of aluminum at 170A to about 840A.

A model of the grazing-incidence scanning monochromator designed for flight on the Orbiting Solar Observatory-1 was

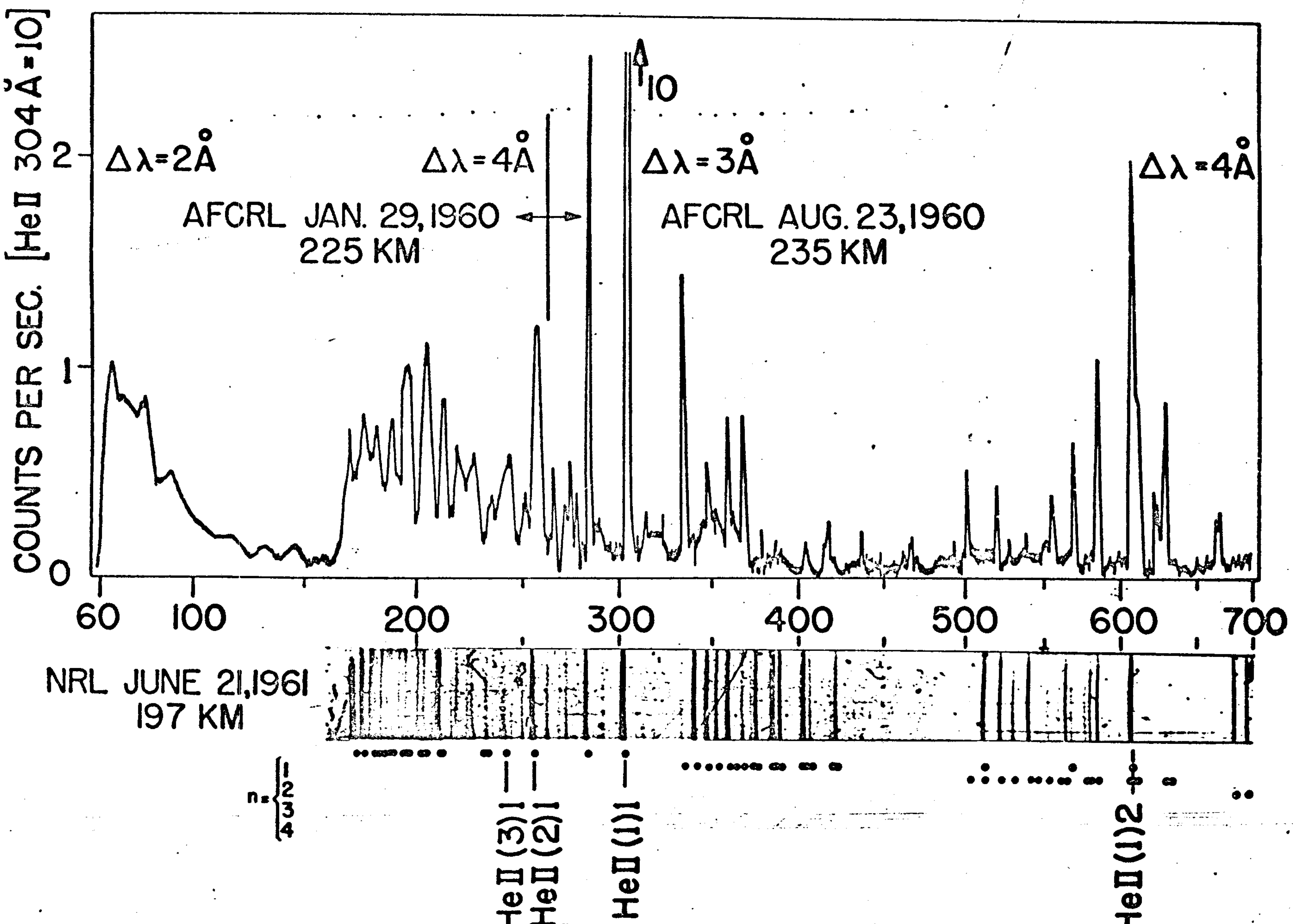
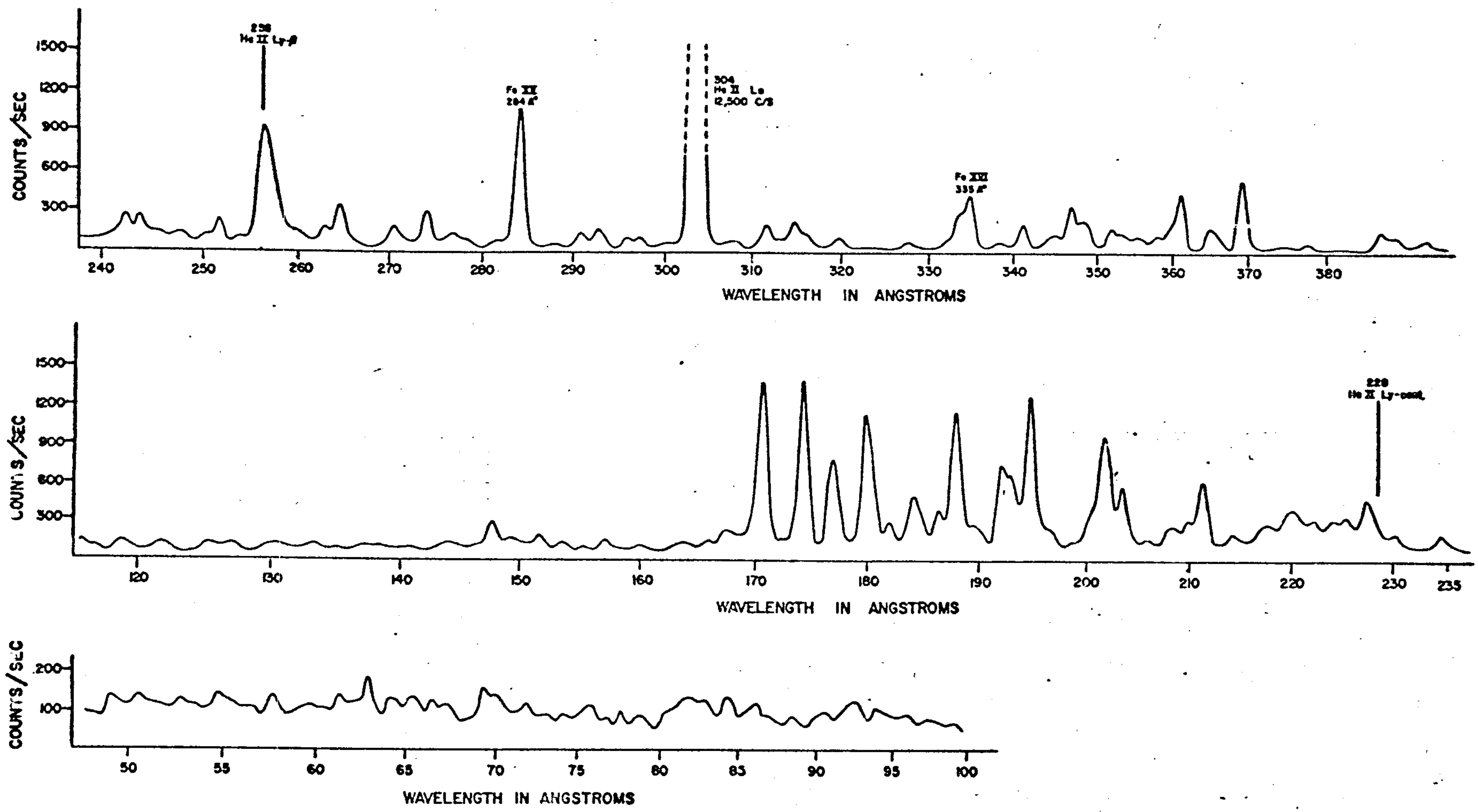


Figure 7. Comparison of Solar EUV Spectra Obtained by Hinteregger and Co-workers and Tousey and Co-workers, from Rocket Flights, January 29,1960 and June 21, 1961, respectively

flown on an Aerobee Rocket on September 30, 1961 (Neupert and Behring [14]). During operation the spectrometer was pointed at the center of the solar disk so that radiation from the entire solar disk and inner corona passed directly through the entrance slit and struck a concave grating mounted in grazing-incidence, the angle of incidence being 88°. The grating, an original ruled in a special glass by the Nobel Institute in Stockholm, had 576 lines per millimeter on a blank of one meter radius of curvature. The exit slit and detector were mounted on a carriage which was driven on a circular rail so that the exit slit scanned along the Rowland Circle, where the spectrum was focused, from 10-400A. The 50 micron entrance and exit slits provided a spectral passband of 1.7A and permitted resolution of lines 0.85A apart. The detector was a windowless photomultiplier with a tungsten photocathode to minimize response to wavelengths above 1500A, and to reduce changes in sensitivity due to variations of the emission properties of the cathode. In flight the instrument proved to be very quiet. With no electromagnetic radiation entering the entrance slit the instrument recorded one spurious count in eight seconds of time.

From the spectrum shown in Figure 8 it can be seen that there is good agreement with the spectra of Hinteregger and Tousey from 170-400A. It has been possible, by combining several scans, to obtain evidence for line structure (Neupert [15]) in the neighborhood of 50A. (Shown as the lower trace in Figure 8).



SOLAR SPECTRUM
SEPT 30 1961

TIME 14:33 (GMT) ALT. 201 TO 216 KM

Figure 8. Spectra of Solar EUV Spectra from GSFC Rocket Flight September 30, 1961

There was also indication of similar line structure in Hinteregger's spectrum of January 29, 1960. Both the NRL and AFCRC groups recently have obtained superior spectra extending down to about 40A.

For the OSO-1 flight spectrometer, calibrations were performed by comparing the value obtained by exposing the entire instrument to a beam of monochromatic radiation of a measured intensity and by evaluating the components of the instrument (gratings, detector, etc.), and computing the sensitivity. The first approach was followed at 44A using a proportional counter for determining the source intensity. The second method was applied at longer wavelengths (80-400A). In addition, comparisons were made with the solar fluxes obtained by Hall, Damon and Hinteregger [16]. The comparisons could only be made in the region of overlap, 250A to 400A, and were only meaningful if the solar radiation was the same. The 2800-Mc mean daily flux recorded by the National Research Council, Ottawa, Canada, was used as an independent estimate of solar flux to choose the satellite data to be compared. A best fit was made between these methods of estimating the spectrometer sensitivity and yielded values of 8.0×10^5 photons cm^{-2} count^{-1} at 335A and 4.5×10^5 photons cm^{-2} count^{-1} at 284A.

A spectrum obtained from the OSO-1 flight of the spectrometer over wavelengths of 170A to 400A is shown in Figure 9. The brightest emission line in the region from 170A to 340A is the Lyman-alpha line of ionized helium at 304A. In addition,

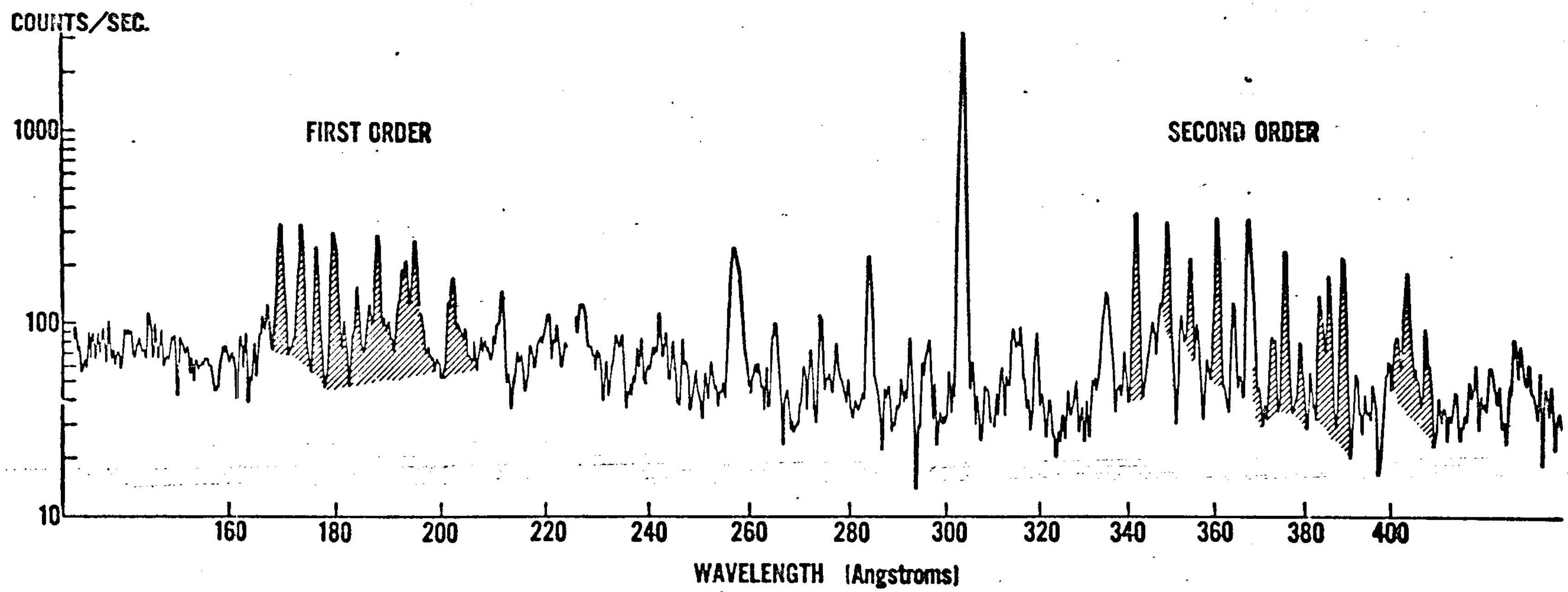


Figure 9. Typical Solar Spectrum (170A-400A) from OSO-1

numerous other emission lines appear with combined flux comparable to, or somewhat greater than, that of the helium line. Resonance lines of heavy ions (Mg through Fe) are expected in this region, leading to attempts (Zirin, Hall and Hinteregger [17]), (Neupert and Behring [14]), to identify the more prominent features of the spectrum in terms of such lines. OOther than the 304A line of He II Lyman-alpha, the only lines identified with relative certainty are the 284A line of Fe XV and the 335A line of Fe XVI.

As mentioned before, the months of March and April of 1962, were ideal for a study of the solar EUV spectra in that observations could be made on both a quiescent and a disturbed solar atmosphere. During the second week in March the sun was especially quiet, the sunspot number being zero on 11 March. As the month progressed the solar rotation carried several centers of activity across the visible hemisphere of the sun. Definite enhancements in the solar spectrum were associated with these centers of activity.

Figure 10 presents two scans of the EUV spectrum which were obtained with a separation in time of approximately ten days (Neupert, Behring and Lindsay [18] .) During the first of these observations only one small region of activity was present on the solar disk. In spite of this low level of activity it is observed that the Fe XV and Fe XVI lines persist as two of the more prominent features of the spectrum. The second spectrum

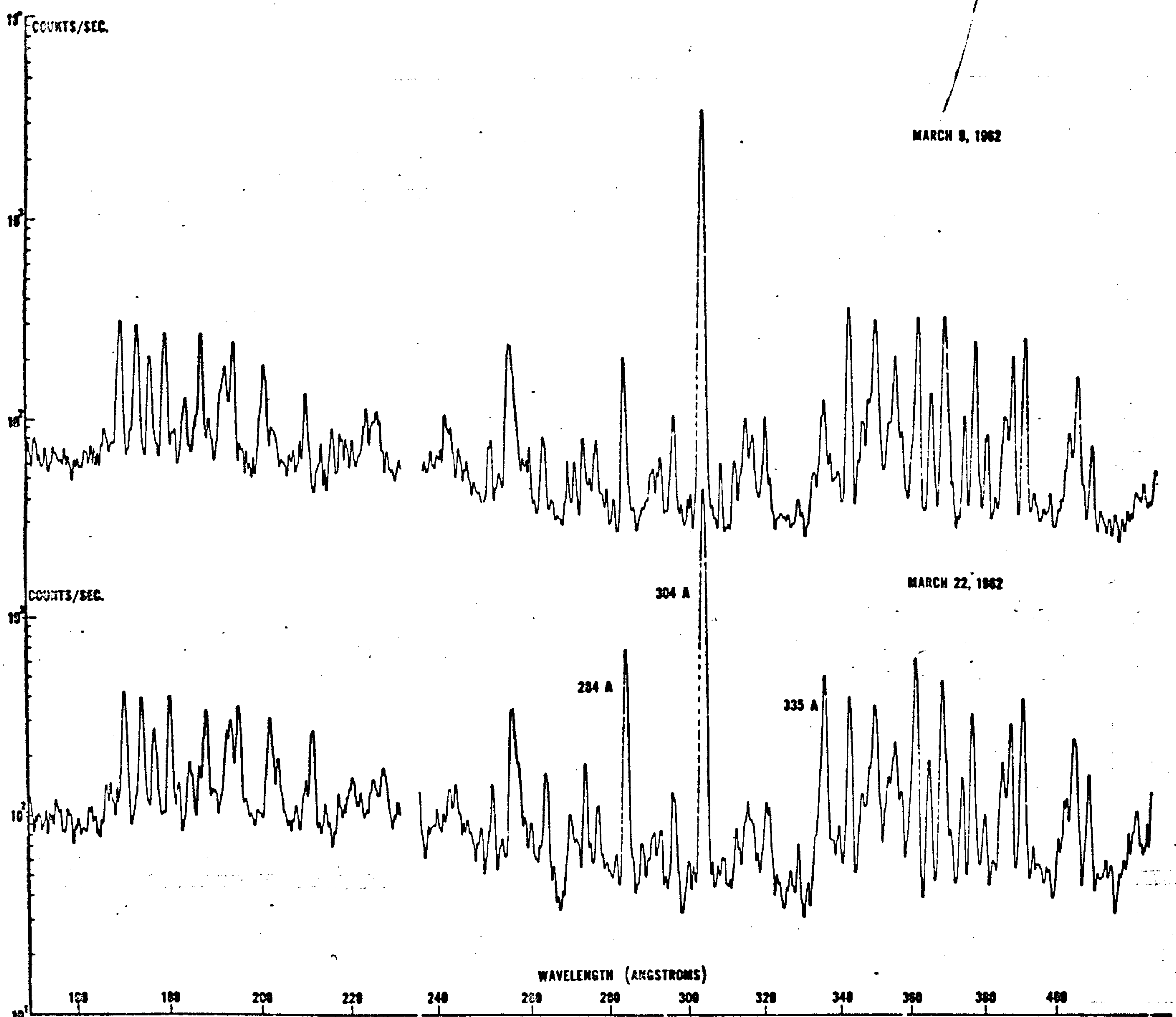


Figure 10. Comparison of Two Spectra Representing "Quiet" and "Active" Sun

was obtained while several large and well-developed centers of activity were present on the disk. Comparing these two spectra, we observe that the emission lines have increased in intensity, but not all by the same amount. The Fe XV and Fe XVI lines, already prominent even in the absence of solar activity, have increased in intensity appreciably more than any other line observed with certainty in this spectral range. The He II line has also increased, but by a lesser amount.

The relationship of these observed counting rates to several ground-based measurements of solar activity is presented in Figures 11 and 12. In Figure 11, the He II radiation is compared with daily values of the solar flux at 2800-Mc, and with the Zurich Provisional Relative Sunspot Number (ZPRSN). Also shown is an estimate of the calcium plage area, each area being weighted by the estimated intensity of the area on scale from 1 to 5. Values for this computation were supplied by the McMath-Hulbert Observatory. In Figure 12, the daily values of solar flux at 2800-Mc and the Zurich Provisional Relative Sunspot Number are compared with radiation due to the coronal lines of Fe XV (284A) and Fe XVI (335A). The estimated calcium plage intensity is also shown.

As would be expected, the effect of flares upon the solar flux near 300A was not as striking as for the 10A X-ray region of the spectra. This is illustrated by data shown in Figure 13 for a class-2 flare that occurred at approximately 2000 UT the 20 April 1962. Coinciding closely with the H-alpha flare there

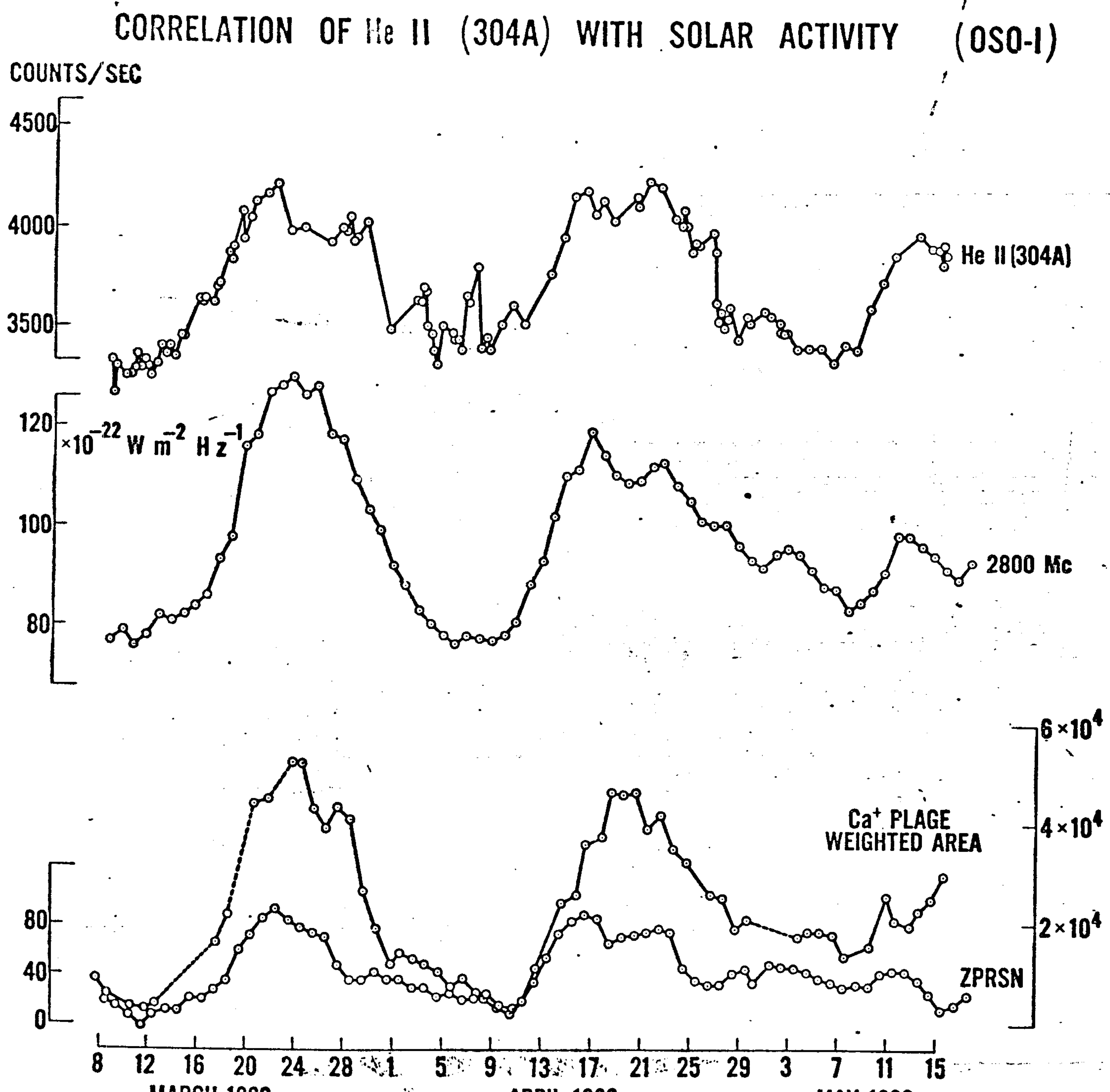


Figure 11. He II Lyman-alpha Line Compared with Ground-based Measurements of Solar Activity

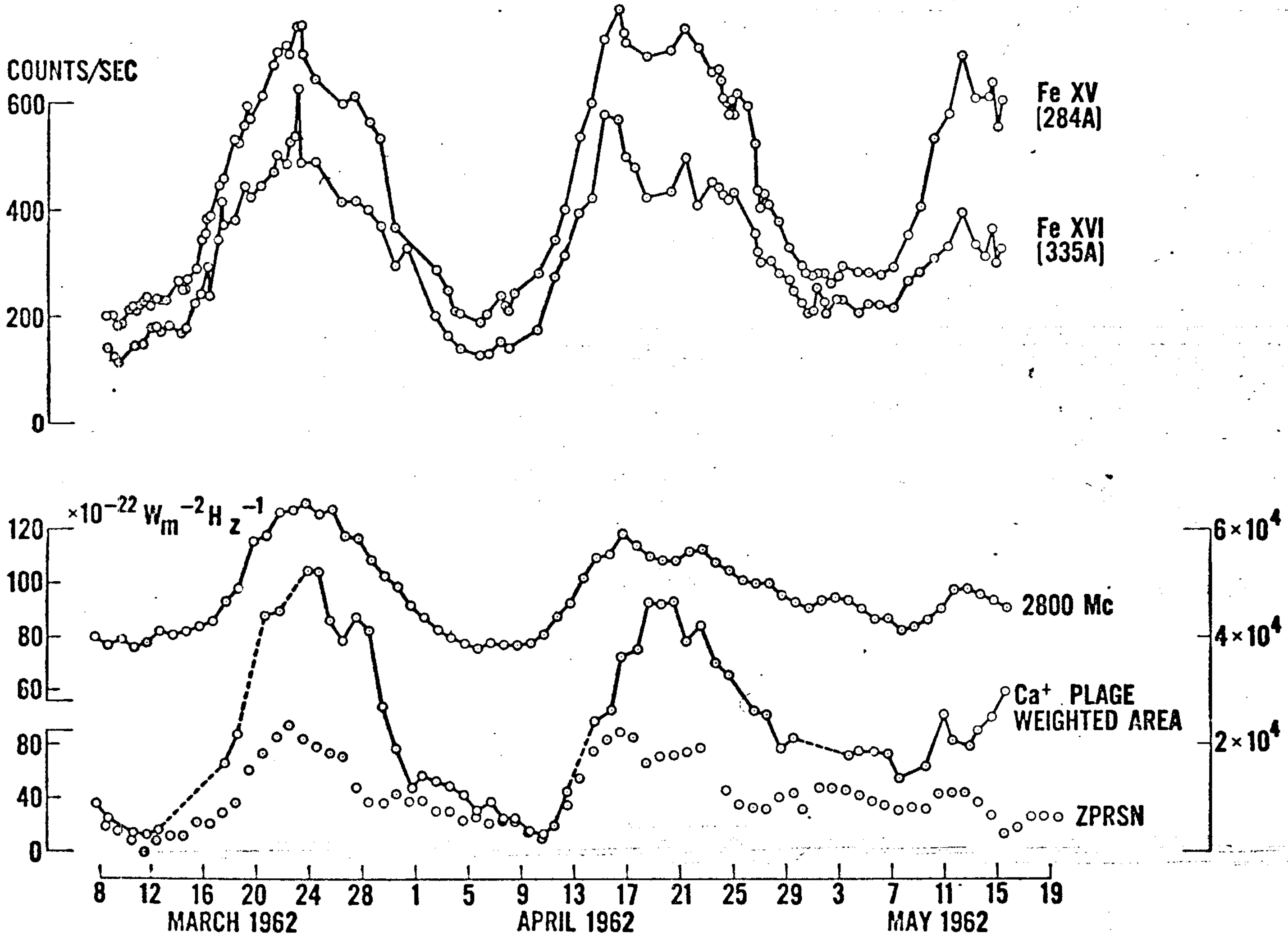


Figure 12. Fe XIV and Fe XVI Lines Compared with Ground-based Measurements of Solar Activity

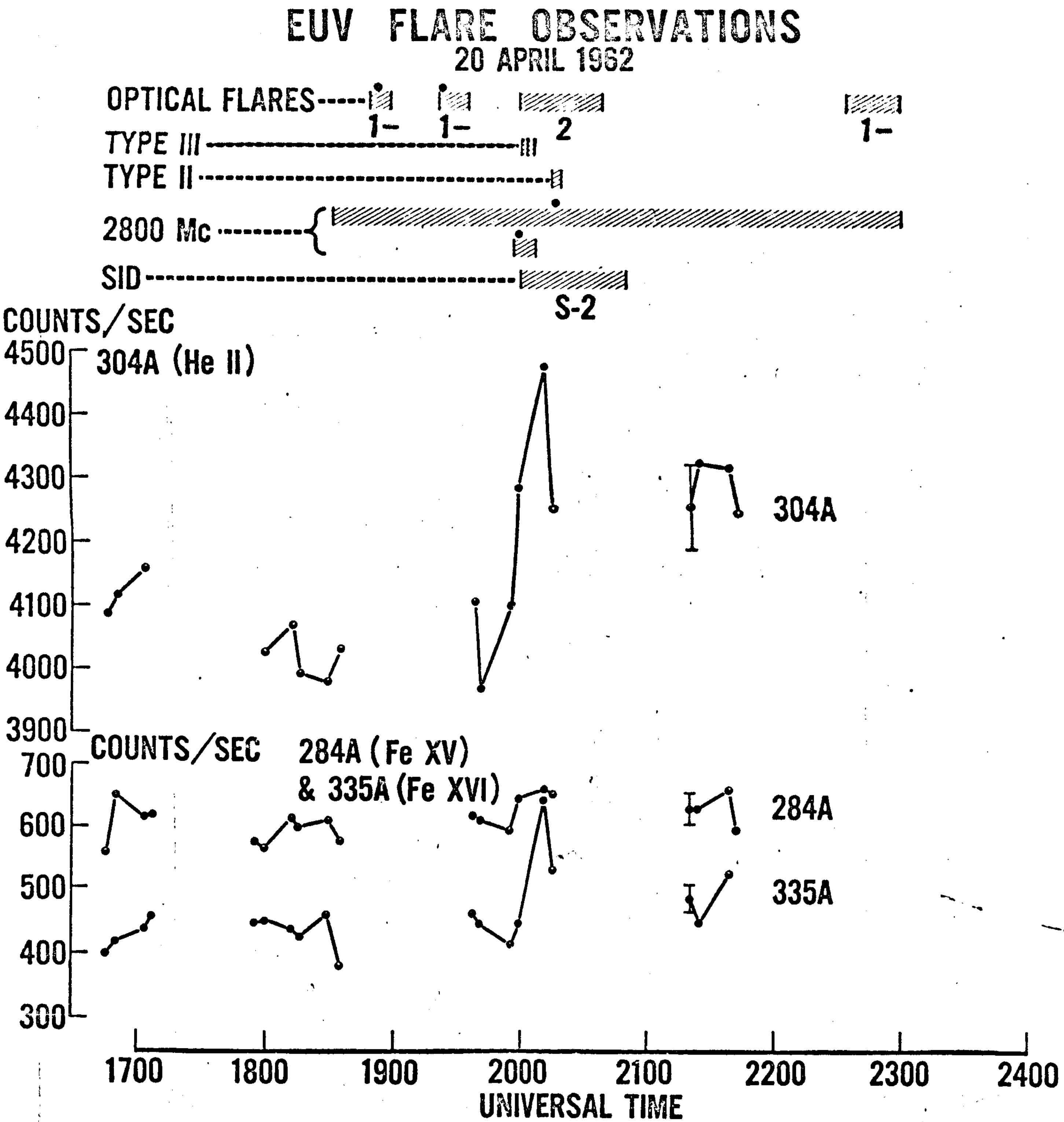


Figure 13. Enhancement of EUV Lines During Class-2 Flare on April 20, 1962

was an enhancement of approximately 12% in the He II 304A flux, 10% in the Fe XV 284A flux, and 50% in the Fe XVI 335A flux. Recalling that even a small flare usually results in an 10A X-ray enhancement of a factor of five or greater, these increases around 300A appear rather small. Of the dozen or so flares studied to date (Neupert [16]) these observations are typical.

The spectral lines chosen for presentation here were selected because they are reliably identified with particular ions, not because they convey more than any other line in the spectrum the changes in solar flux which occur with the appearance of plage areas. In terms of fractional changes in intensity, these three lines represent the extremes which have thus far been observed in the spectral region from 171A to 400A; only a few faint lines have smaller non-flare variations than the He II Lyman-alpha line, while no other lines have increases as great as those observed for 284A and 335A. A summary of the average increases in counting rates for the period from 9 March to 23 March 1962, a period of increasing solar activity, is given in Table 1. The increase, weighted by the intensity of each line, is computed for the range from 171A to 305A, using sixty reliably observed lines. The increase in the range from 305A to 400A can only be estimated because of the masking effect of second order images above 342A. The values given in Table 1 are, of course, appropriate only for the particular interval in time for which they were computed.

The initial analysis of only three lines (He II 304A, Fe XV 284A, Fe XVI 335A) already indicates that the relative prominence of spectral lines may depend upon the age of the center of activity which is responsible for the increased radiation. As an example of this, one may observe (Figure 12) that the maximum emission in the Fe XV apparently occurs later in time than the maximum for the 2800-Mc radio flux or for the plage areas observed during March, April and May. In addition, to such a slowly changing effect, one may note that localized perturbations appear (7-9 March and 16-17 April) for which the relative increases are considerably different for the helium and the iron lines. It appears that in these instances we are observing phenomena localized at particular levels in the solar atmosphere.

TABLE I

INCREASES IN SOLAR EUV SPECTROPHOTOMETER COUNTING RATES

9 March 1962 to 23 March 1962

SPECTRAL RANGE	AVERAGE COUNTING RATE INCREASE
171A - 228A	55%
229A - 300A	80%
229A - 305A	52%
305A - 400A	50%(estimated)

SUMMARY

The principal observations discussed may be summarized as follows:

(1) A slowly-varying component has been observed in the solar X-ray flux that correlates with the slowly-varying component of the 2800-Mc solar radiation and with the plage activity. It is evident that plages are the major source of solar X-rays for relatively quiet sun conditions.

(2) The lowest X-ray flux that has been measured from satellites was for $\lambda < 8A$, 3.6×10^{-5} ergs cm^{-2} sec^{-1}; for $\lambda < 11A$, 1.8×10^{-4} ergs cm^{-2} sec^{-1} . This may be considered as an upper bound from a "quiet" sun.

(3) When the sun emits an X-ray flux of $\lambda < 8A$ in excess of 0.6×10^{-3} ergs cm^{-3} sec^{-1} some optical indication of activity is usually observed. If the flux is in excess of 2×10^{-3} erg cm^{-2} sec^{-1} radio fadeout and other SID phenomena occur.

(4) Variations of a factor of two in X-ray emission have been observed to occur in the order of one second.

(5) Active prominences and bright limb sources have been observed to produce X-ray events.

(6) The X-ray flux from the sun is quite variable. Out of several hundred hours of observation only six hours were found in which the X-ray flux did not vary by more than five percent.

(7) The flare associated X-ray spectrum was observed to harden as compared with pre-flare spectrum.

(8) No definite statement can be made at this time concerning correlation of X-ray events with H-alpha flares since X-ray events have been observed when no H-alpha event was reported although observations were presumably being made.

(9) The He II (304A) emission is enhanced by a factor of about 33% during a period when the Zurich Provisional Relative Sunspot Number increased from zero to a maximum of 94 and the 2800-Mc flux varied from approximately 76 to 125 x 10^{-22} wm^{-2} Hz^{-1}.

(10) The Fe XV (284A) and Fe XVI (335A) coronal lines were enhanced during the same period by a factor of approximately four.

(11) The enhancements of He II (304A) and Fe XV (284A) and Fe XVI (335A) due to plage activity were much larger than enhancements due to flares that occurred during the three-month interval of the observations.

(12) The variations in intensity of the He II (304A), Fe XV (284A) and Fe XVI (335A) represent the extremes observed. If one averages sixty of the reliably observed lines between 171A and 342A the enhancement is between 50% and 80% for the time interval 9 March to 23 March.

(13) Although there appears to be a gross correlation between solar activity indices (such as 2800-Mc flux) and the He II, Fe XV and Fe XVI fluxes, there are indications that the relative prominence of the spectral lines may depend upon the age of the center of activity.

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CAPTIONS

Figure 1 - OSO-1 Ion Chamber Response

Figure 2 - OSO-1 Observation of Solar X-ray Flux for a Quiet Period

Figure 3 - Comparison of X-ray Flux with 2800-Mc Radio Measurements

Figure 4 - Typical Transient X-ray Events Observed by OSO-1

Figure 5 - X-ray Events for Period March 7 to 14, 1962, Observed by OSO-1

Figure 6 - Comparison of X-ray Events in X-rays and 2800-Mc Flux showing Larger Percentage Change in X-rays

Figure 7 - Comparison of Solar EUV Spectra Obtained by Hinteregger and Co-workers and Tousey and Co-workers, from Rocket Flights, January 29, 1960 and June 21, 1961, respectively

Figure 8 - Spectra of Solar EUV Spectra from GSFC Rocket Flight September 30, 1961

Figure 9 - Typical Solar Spectrum (170A-400A) from OSO-1

Figure 10 - Comparison of Two Spectra Representing "Quiet" and "Active" Sun

Figure 11 - He II Lyman-alpha Line Compared with Ground-based Measurements of Solar Activity

Figure 12 - Fe XIV and Fe XVI Lines Compared with Ground-based Measurements of Solar Activity

Figure 13 - Enhancement of EUV Lines during Class-2 Flare on April 20, 1962